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Effects of flat and elongated particles upon properties of mixtures containing glass aggregates

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EFFECTS OF FLAT AND ELONGATED PARTICLES

UPON PROPERTIES OF MIXTURES

CONTAINING GLASS AGGREGATES

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ABSTRACT

As a possible solution for the rapidly proliferating problem of waste glass disposal in the United States, glass is being considered for use as aggregate in bituminous concrete mixtures.

Crushed waste glass particles, and crushed bottle glass particles in particular, are more angular, much smoother, and contain a higher percentage of flat and/or elongated particles than conventional rock aggregate particles. Because of the differences in shape and surface texture, glass aggregate may require different gradations than those found suitable for conventional rock aggregate. Objectives of this research were to determine gradations which result in maximum density for aggregates consisting entirely, or in part, of glass; to evaluate the effect of angularity and sphericity of glass particles upon gradations giving maximum density; to find whether maximum density gradations of glass aggregate can be used to produce asphaltic mixtures meeting Marshall design criteria and, if necessary, determine the modifications in gradations necessary to produce asphaltic mixtures meeting Marshall design criteria; and to determine effects of angularity and sphericity of glass particles upon properties of asphaltic mixtures.

A series of dry density tests on crushed bottle glass at various gradations were conducted to determine a maximum density gradation. A series of dry density tests were also conducted for glass spheres to study the effects of angularity and sphericity upon the maximum density gradation. In order to isolate the effects of angularity and sphericity

of the coarse sized glass particles, different types of coarse glass aggregate were used in combination with fine sized conventional aggregate and a series of dry density tests were conducted for each combination. Dry density tests were also conducted for several gap-gradations to study the effects of eliminating certain sizes of crushed bottle glass on the density of the dry aggregate.

Using crushed bottle glass as aggregate, Marshall tests were conducted at different asphalt contents to determine whether Marshall design criteria could be met for a maximum density gradation, or a modification of it. Additional Marshall specimens were made substituting different types of glass aggregate for crushed bottle glass to determine effects of angularity and sphericity of glass particles upon properties of asphalt mixtures.

For a dense-graded dry aggregate, the angularity and sphericity of the glass particles affect the gradation that will give maximum density. The more angular the glass particles, the larger the percentage of fines necessary for the maximum density gradation; while the more spherical the glass particles, the wider is the range of gradations giving maximum density, or close to it. The range of gradations is considerably larger for a combination of glass and conventional aggregate than for an all-glass aggregate. The properties of angularity and sphericity of glass particles also affect the void content of the maximum density gradation, a more angular and non-spherical glass aggregate giving a higher void content. Gap-grading does not seem to have a significant effect on the maximum density gradation, for a dense-graded mixture, although somewhat higher density gradations may be obtained by eliminating certain size fractions.

The maximum density gradation for crushed bottle glass does not produce an asphaltic mixture meeting Marshall design crieteria, but the gradation can be modified to produce an asphaltic mixture that will meet these criteria.

Dry density tests for dense-graded aggregate does not give a good indication of densities obtained in asphaltic mixtures using the same aggregate.

Sphericity of coarse sized glass particles has little effect upon the Marshall properties, but a decrease in angularity decreases the stability and void content while increasing the flow. The strength of a glass aggregate asphaltic mixture appears to derive almost entirely from the interlocking resistance developed between particles.

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I. INTRODUCTION

A. Statement of the Problem

Solid waste disposal is a rapidly proliferating problem in the United States. As a possible solution for the problem of waste glass disposal, glass is being considered for use as aggregate in bituminous concrete mixtures (1,2,3).

Crushed glass aggregate differs from rock aggregate in several ways, but perhaps the most pronounced and important differences are in the properties of shape and surface texture. Whereas most of the rock aggregate particles are fairly equidimensional, crushed glass particles, and crushed bottle glass particles in particular, tend to be flat and elongated, and very angular. Also, the surface texture of glass aggregate is very smooth compared to that of any rock aggregate. Although there is a large difference in surface textures among natural rock aggregates, such as river gravel or crushed limestone, they generally have rougher surface texture than that of glass.

Because of the differences in the above mentioned properties of glass and rock aggregates, a different gradation than is normally used for rock aggregate may be required to provide the best bituminous concrete mixture. Although for most mixtures, a gradation giving close to maximum density is desired, this may not be the case when glass aggregate is used. Gradations which are well suited for aggregates containing primarily equidimensional particles may not be best for aggregates such as waste glass which contain large percentages of flat and/or elongated particles.

B. Objectives

The objectives of this research were as follows:

1. Determine gradations which result in maximum density for aggregates containing glass particles having varying degrees of angularity and sphericity. Aggregates consisting entirely of glass as well as combinations of glass and conventional aggregates will be used.
2. Determine the effect of angularity and sphericity of glass particles upon gradations giving maximum density.
3. Determine whether maximum density gradations of glass aggregates can be used to produce asphaltic mixtures meeting Marshall design requirements.
4. If necessary, determine modifications in gradation of glass aggregates needed to produce asphaltic mixtures meeting Marshall design requirements.
5. Determine effects of angularity and sphericity of glass particles upon properties of asphaltic mixtures such as Marshall stability, flow and void content.

II. BACKGROUND

Since angularity, sphericity and surface texture are perhaps the most important properties to consider when using crushed bottle glass as an aggregate, it seems worthwhile to summarize their effects on the properties of bituminous mixtures and on maximum density gradations.

Aggregate shape is many times used to describe both the angularity and sphericity of the aggregate. In this paper angularity will refer to the relative sharpness of the edges and corners of an aggregate particle, while sphericity is a measure of the ratio of the surface area to volume of an aggregate particle, the ratio being smallest for a sphere and largest for a flat and elongated particle.

A. Effects of Particle Shape and Surface Texture Upon Properties of Bituminous Mixtures

1. Stability

The stability of bituminous concrete is affected by the angularity, sphericity, surface texture, and different combinations of these properties. It is hard to separate the effects of angularity and surface texture of the aggregate, since in most of the studies done, the angular material is obtained by crushing, which tends to give a rough surface texture, and the rounded material is usually river gravel and sand which has a smooth surface texture. Thus, crushed material generally has a high degree of angularity and surface roughness while gravels tend to have smoother and rounder particles. It is generally recognized however, that higher angularity of an aggregate increases stability by increasing the interlocking resistance that is developed between particles in the bituminous mixture; and that a rough surface texture increases stability by increasing the frictional resistance that is developed between aggregate particles. The frictional and interlocking resistance effect is greatest for a dense-graded mixture. Hargett (4) found that for a dense-graded bituminous mixture, about 50 percent of the shearing resistance is developed by frictional resistance and about 25 percent is developed in the form of interlocking resistance.

Although stability is increased through greater angularity and rougher surface texture of the aggregate for all sizes, for dense-graded mixtures this effect is much more pronounced in the fine aggregate sizes. Studies by Herrin and Goetz (5) and Shklarsky and Livneh (6) both stated that using a crushed fine aggregate in the place of a natural sand increased the stability more than substituting a crushed coarse aggregate for a rounded coarse aggregate.

The main influence of sphericity on stability of bituminous mixtures is that the occurance of flat and elongated particles may decrease the stability. Li and Kett (7) stated that if a bituminous mixture contains a sufficient proportion of particles whose width to thickness, or length to width, equals or exceeds three to one, its stability is adversely affected. It was concluded that the percentage of flat shaped particles that may be included without causing undesirable effects is as high as 30 percent and may possibly be 40 percent. This decrease in stability may be explained by particle alignment. Puzinauskas (8) concluded that regardless of type of aggregate or method of compaction, aggregate particles tend to become axially aligned in a direction perpendicular to the direction of the compacting force, and a more pronounced effect on mixture properties is produced by particle alignment in mixtures containing elongated or flattened particles than in mixtures containing rounded particles.

2. Durability

The durability of a bituminous mixture is influenced by the aggregate primarily due to the effect of aggregate properties on the voids in the mixture and the effect on the optimum asphalt content. It is well known that the controlling factor as to the amount of voids in the mineral aggregate in a bituminous mixture is the aggregate gradation. However, if the gradation, method of compaction, and asphalt content are held constant, the void content will vary with the shape and surface texture of the aggregate. In general, it can be said that, for a constant gradation and method of compaction, the minimum void content will increase as the angularity of the aggregate increases, the aggregate becomes less spherical, and its surface texture becomes rougher.

For a constant gradation, the optimum asphalt content will increase as the angularity of the aggregate increases, as it becomes less spherical, and as its surface texture becomes rougher.

Studies have shown that the substitution of crushed fine aggregate for natural sands has had a greater effect on increasing minimum void content and optimum asphalt content than the substitution of crushed coarse aggregate for rounded and smooth coarse aggregate. Perhaps the best explanation of the dominant effect of the fine aggregate was given by Lefebvre (9) who writes as follows:

> Although each of the fractions which make up the mineral aggregate has a considerable influence on the characteristics of a paving mixture, the fine aggregate as usually referred to can be considered as the most critical component. Its quantity and characteristics control to a large extent the percentage of voids in the total aggregate and affect also the stability as well as the amount of bitumen which can be incorporated...The fine aggregate should be such that by its rough texture, angularity of particles and gradation, it will develop a high stability while maintaining a relatively high percentage of voids in the mineral aggregate at a bitumen content producing the required percentage of voids in the compacted mix.

3. Flexibility

The sphericity of the aggregate can influence the flexibility of a bituminous mixture. Lee and Marwick (10) found that mixtures made with flaky particles offer resistance to deformation 50 percent greater than that offered by mixtures made with cubical stones under otherwise identical conditions.

4. Skid Resistance

The angularity and surface texture of the aggregate somewhat affects the skid resistance of a bituminous mixture. Moyer and Shupe (11) found that friction values for rounded aggregate were about 25 percent lower than those for angular aggregates in wet pavement tests.

5. Workability

The workability or ease of compaction of a bituminous mixture can be very much affected by the angularity, sphericity, and surface texture of the aggregate. Workability decreases as the aggregate angularity increases, as its surface texture becomes rougher, and as the aggregate becomes less spherical. This is to be expected since these same properties increase stability, and higher stability mixtures are more difficult to compact.

B. Effects of Particle Shape and Surface Texture Upon Maximum Density Gradations

The effect of angularity, sphericity and surface texture on minimum voids in an aggregate is fairly well known when the gradation is held constant. As mentioned previously if the aggregate becomes more angular, less spherical, and rough, its void content will increase. However, the individual effects of the aggregate properties are not so well known. Powers (12) stated that spheres have the smallest specific surface area for a given nominal size and a random aggregation of spheres has the least percentage of voids for a given grading. He also concluded that for gradings within a given size range, and having ratios of fine to coarse within the usual range, particle shape has a much larger effect on voids content than does grading.

What gradation is necessary to produce maximum density when the aggregate contains a large amount of flat and elongated particles is not known, since most of the work done on maximum density gradations has been with either a rounded or angular aggregate, but not a flat and elongated one. Smith and Kidd (13) suggested that when computing an ideal grading from the formula:

$P = (\frac{d}{D})^n$ where P is the accumulative percentage passing a sieve of size d for an aggregate having a maximum size D.

a value of n = 0.3 be used with angular flat and elongated crushed aggregate and a value of n = 0.5 be used with spherically shaped natural gravels. The value of n = 0.3 would give a gradation containing more fines which tends to agree with the dominant effect of fine aggregate idea stated by Lefebvre (9) and others.

III. EXPERIMENTAL PROCEDURES

A. General Approach

A series of dry density tests were conducted on crushed bottle glass at various gradations to determine a maximum density gradation. It was not known whether the maximum density gradation would give a satisfactory bituminous mixture, but it was to be used as a starting point. To study the effects of angularity and sphericity upon the maximum density gradation, dry density tests were also conducted using glass spheres as aggregate.

In several field installations using glass aggregates (3), conventional fine aggregates were blended with the glass. Also, after determining the percentage of flat and elongated particles in crushed bottle glass, it was found that the majority of flat and elongated particles were found in the coarser sieve sizes. To evaluate the effects of changes in percentages of these sizes, tests were conducted on mixtures using sand and limestone filler for the fine sizes and glass for the coarse sizes. Three types of glass were used. Broken bottle glass has a smooth surface texture, high degree of angularity and large percentage of flat and elongated particles. A mixture of tempered glass and drain cullet was also used since the particles are smooth and angular but possess a higher degree of sphericity. Finally, glass beads were used, representing a material with smooth surface texture but low angularity and a high degree of sphericity. Through this approach, the effects of angularity and sphericity upon density of mixtures containing no asphalt could be isolated.

Using crushed bottle glass as aggregate and the gradation giving maximum density, a Marshall mix design procedure was carried out to determine the optimum asphalt content. Then modifications could be made in the gradation as necessary to meet Marshall design requirements.

Finally, when a mixture meeting Marshall design requirements was obtained, substitution of glass spheres or drain cullet could be made in the mixture to determine the effects of angularity and sphericity upon the properties of asphaltic mixtures.

B. Materials

All of the crushed bottle glass aggregate used in this study was obtained by crushing various types of glass containers, but primarily bottles. The initial treatment of the bottles consisted of a hot water bath in which labels and all other foreign materials were removed. After allowing the bottles to dry, they were crushed in a hammermill. Some of the crushed glass was then placed in the Los Angeles abrasion machine with varying numbers of steel balls and for various time periods to obtain the finer sizes. The crushed glass was separated into nine different size fractions by sieving; the sizes ranged from material passing the 1/2-in. sieve and retained on the 3/8-in. sieve to material passing the No. 200 sieve. Sieving was done using eight inch diameter sieves and Ro-Tap sieve shakers.

Random samples from the larger size fractions were tested for percentage of flat and/or elongated particles using Corps of Engineers Methods CRD-C 119 and CRD-C 120. One hundred to three hundred particles of each of the larger size fractions were obtained by sub-division of the random samples, with the larger particle sample size being used for the smaller size fractions. The length, width, and thickness of the particles were measured, and the particles were classified based on the ratios of length to width and width to thickness. A flat particle was defined as having a width to thickness ratio of three or greater, and an elongated particle was defined as having a length to width ratio of three or greater. Results showed that a high percentage of the particles in the 1/2-in. to 3/8-in. size fractions were flat, but the percentage of flat particles decreased as the size of the sieve openings on which the particles were retained approached the wall thickness of the bottles; the minimum percentage of flat and/or elongated particles was found in the material retained on the No. 8 sieve, which is the sieve size closest to the wall thickness of the bottles. The percentage of flat particles began to increase slightly for the material passing the No. 8 sieve, and a microscopic investigation of the materials passing the No. 50 sieve indicated that they also contained some flat and/or elongated particles. However, the majority of flat and/or elongated particles were found in the coarser fractions.

The drain cullet and crushed tempered glass were used in an effort to isolate the effect of sphericity of the glass aggregate, since the drain cullet and crushed tempered glass were fairly equidimensional, but angular. Drain cullet is formed when molten waste glass is quenched in water forming a fairly equidimensional, but angular shape. Drain cullet was used in the 1/2-in. to 3/8-in. size fraction, because the tempered glass in that size fraction contained too many flat particles. Tempered glass when crushed, forms nearly equidimensional and very angular particles in the size ranges 3/8-in to No. 4 and No. 4 to No. 8 fractions, these sizes being closest to the thickness of the tempered glass. Sizes above or below this contain a significant amount of flat particles. Because of this, the minimum size of tempered glass used was material retained on the No. 8 sieve.

A determination of the percentage of flat and/or elongated particles was performed on drain cullet and tempered glass for the sizes used plus the No. 8 to No. 16 fraction, as well as a microscopic investigation of material passing the No. 16 sieve. The results showed a negligible percentage of flat and/or elongated particles in the size range of 1/2-in. to No. 8, but a significant percentage of flat particles in the No. 8 to No. 16 fraction. The microscopic investigation of material passing the No. 16 sieve also showed a significant amount of flat and/or elongated particles.

The glass spheres were used to study the effect of angularity and sphericity on the maximum density gradation. The glass spheres were obtained form several sources and the sizes used were the same as that for the crushed bottle glass; material ranging from that passing the 1/2-in. sieve and retained on the 3/8-in. sieve to that passing the No. 200 sieve. A microscopic investigation was made of the smaller sizes which showed that most of the material retained its sphericity for all sizes.

Meramec river sand and mineral filler were used in combination with each of the three previously discussed glass aggregates to study the effect of angularity and sphericity of the coarse aggregate. The sand was a rounded material obtained from the Meramec river, and the mineral filler consisted of limestone dust. The sizes of sand used ranged from material passing the No. 8 sieve and retained on the No. 16 sieve to material passing the No. 100 sieve and retained on the No. 200 sieve. All of the material passing the No. 200 sieve consisted of limestone dust.

Data for all of the various aggregates is shown in Tables I and II.

The asphalt used in this research was an 85-100 penetration asphalt cement furnished by the Shell Oil Company. It was produced from a West Texas crude oil. Properties of the asphalt cement are listed in Table III.

Calcium hydroxide was used as an anti-stripping additive when making bituminous mixtures with all-glass aggregate. The amount added consisted of one percent by weight of the glass aggregate.

C. Testing Methods

The gradations and procedures were the same for each series of dry density tests to determine the maximum density gradation. Only the type of aggregate was changed for each series.

The following steps and procedures were used for the various series of dry density tests:

1. Each size fraction of material was weighed so that the total mixture would meet the desired gradation.

2. The mixture was then placed in a hand operated mixer and mixed until a thoroughly integrated mixture was obtained. The mixer gave a mixing action much like that of a small concrete mixer. The hand operated mixer consisted of a 5-gallon drum mounted on a rotating shaft, which in turn was mounted on a stand; the rotating shaft and drum were inclined at approximately 15° above horizontal. Two mixing blades were mounted on the interior walls of the drum directly across from each

other, and a lid was placed on the drum to avoid spilling of the aggregate while mixing.

3. After mixing, the aggregate mixture was scooped out of the mixer and placed in a flat pan, with care being taken not to cause any segregation during transfer. The transfer process also served as a check to insure that the aggregate was thoroughly mixed.

4. The aggregate mixture was then scooped into a 0.1 cubic foot metal cylindrical measure until the measure was overflowing. The measure was then placed upon a spring mounted platform with an attached mechanical vibrator. The measure was vibrated for a time period of 30 seconds while keeping it filled. The excess material was then leveled off and the measure and aggregate were weighed. Mechanical vibration for 30 seconds was found to give the same amount of compaction as the rodding procedure specified by ASTM C 29 for determining unit weight of aggregate having a maximum size of 1 1/2-in. or less.

5. Having previously determined the weight and volume of the measure, the density of the aggregate mixture was then determined. Steps two through five were repeated two more times and the average of the three densities was used.

6. Steps one through five were then repeated for each different gradation until the series was completed.

The Marshall tests were conducted according to procedures specified by ASTM D 1559 with the following exceptions:

1. Immediately after mixing for two minutes in the Hobart Model N-50 mixer, the bituminous mixture was placed in compaction molds. The molds were retained for 30 minutes in an oven at 275 F to insure a

uniform temperature for all specimens at compaction. At the end of this 30 minute retention period, the molds were removed and the mixtures were spaded and compacted according to specifications.

2. A mechanical compaction hammer was used instead of a hand operated compaction hammer.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Dry Density Testing

The gradations for the series of dry density testing were determined from a modification of Talbot's formula (14):

$$P = (\frac{d}{D})^n \times 100$$

where

P = Percent passing a sieve having an opening of d inches

D = Maximum size of the aggregate

n = Grading ratio, an empirical constant for each gradation.

The above formula is considered to give the maximum density gradation when the proper grading ratio "n" is used. The value of the exponent "n" is dependent upon the aggregate's angularity, sphericity, and surface texture and a value of 0.45 or 0.50 is usually used for fairly equidimensional particles. Exponential values of 0.300 to 0.550, in increments of .025, were used in this study. The gradations calculated for the varying grading ratios are shown in Table IV. A study of the table will show that as the exponent increases the amount of coarse material increases, and the amount of fine material decreases in the gradation.

A series of dry density tests were first conducted using crushed bottle glass as aggregate for all sizes. The density and percent voids for each gradation are shown in Table V, and the relationship between variable exponent values and the density or percent voids is shown in Figures 1 and 2.

A series of dry density tests were then conducted using glass spheres as aggregate for all sizes. The results of this series are shown in Table VI and Figures 1 and 2.

Figures 1 and 2 show that sphericity and angularity of the glass aggregate affect not only the exponent at which maximum density occurs, but also the amount of voids present for each gradation. The results of the two series confirm the previously stated information concerning the effect of angularity and sphericity of the aggregate on maximum density gradations. Powers (12) stated that spheres have the smallest specific surface area for a given nominal size and a random aggregation of spheres has the least percentage of voids for a given grading. He also concluded that for gradings within a given size range, and having ratios of fine to coarse within the usual range, particle shape has a much larger effect on voids content than does grading. Both of these statements are very well illustrated by the voids curves for glass spheres and crushed bottle glass. For any gradation, the voids content is much lower for the spheres than for the crushed bottle glass. Also the difference in voids content due to the difference in particle shape is more than twice the difference in voids content due to a difference in grading.

The density curves also agree rather closely with Smith and Kidd's (13) suggestion that an exponent of 0.3 be used with angular, flat and elongated crushed aggregate and an exponential value of 0.5 be used with spherically shaped natural gravels, to determine a maximum density gradation. The smoother surface texture of crushed bottle glass, compared to crushed rock aggregate, could account for the maximum density gradation being at an exponential value closer to 0.4 than 0.3.

During the series of tests on the crushed bottle glass, four of the gradations were sieved again after testing and each size fraction was weighed to determine if there was enough degradation occurring to influence the results. The only noticeable degradation occurring was that of the material retained on the No. 4 sieve, and this was considered insignificant since it was only one percent by weight.

In an effort to study the effects of angularity and sphericity of the coarse particles on the maximum density gradation, three series of dry density tests were run using as aggregate, Meramec river sand and mineral filler in combination with each of the following: crushed bottle glass, glass spheres, and drain cullet and crushed tempered glass. The combinations of aggregates used are shown in Table VII, and the results of the tests are shown in Tables VIII through X and Figures 3 through 8.

A study of the density and void content curves shows that the angularity and sphericity of the coarse particles do have a significant influence on the maximum density gradations. Figure 3 shows that the combination of crushed bottle glass, river sand, and mineral filler has a maximum density gradation very close to that of the series using crushed bottle glass entirely as the aggregate. The slight shift toward a higher exponent for the sand-glass combination can be expected because of the rounded sand particles.

Figure 5 shows that the combination of glass spheres, river sand, and mineral filler has a maximum density gradation close to that of the series using all glass spheres. However, the glass-sand combination has a considerably wider range of exponential values that will give either the maximum density gradation, or close to it. In other words, the curve is flatter at the peak. The slight shift toward a lower exponent for the sand-glass combination is probably due to the rounded river sand being less spherical than the glass beads.

Figure 7 shows that the combination of drain cullet, tempered glass, river sand, and mineral filler has a maximum density gradation close to that of the crushed bottle glass-sand combination, but a range of exponential values giving either a maximum density gradation, or close to it, similar to that of the glass spheres-sand combination. As mentioned previously, drain cullet and tempered glass are angular, but fairly equidimensional, and were used in an effort to separate the influence of angularity and sphericity.

The effects of the properties of angularity and sphericity of the coarse glass particles on the maximum density gradation can be summarized by stating that the angularity of the coarse aggregate affects the exponent at which the maximum density peak occurs while the sphericity of the coarse aggregate affects the flatness of the maximum density curve. The more angular the aggregate, the lower the value of the exponent giving maximum density gradation and the larger the percentage of fines contained in the gradation. The more spherical the aggregate, or the fewer the flat and elongated particles, the wider the range of exponents that will give maximum density gradation, or else close to it.

It should be pointed out that the minimum percent voids were lower for the glass spheres-sand combination than for the crushed bottle glass-sand combination. This is to be expected if the angularity and sphericity of the coarse particles are to influence the void content in the maximum density gradation; however, the void contents were much closer together for the sand-glass combinations than for the two series using all glass aggregate. This seems to indicate that the void content of the maximum density gradation is more dependent on the shape of the fine particles than on the shape of the coarse particles. The minimum void content of the drain cullet, tempered glass, river sand and mineral filler combination was approximately midway between the minimum void contents of the other two sand-glass combinations, which indicates that the properties of angularity and sphericity of the coarse particles equally affect the minimum void content. The more angular and less spherical the particles, the higher the minimum void content.

Because of the rather unusual combinations of flat and elongated particles, angularity, and smooth surface texture found in crushed bottle glass, some gap-graded mixtures using crushed bottle glass as aggregate were tested for density and voids, and the results noted. The first gradation was a radical one using only three sizes increasing from smallest to largest by multiples of ten. The gradation used and the test results are shown in Table XI, as Gradation "A". It can readily be seen that the gradation has a much lower density and higher void content than the maximum density gradation for the series run with variable exponential values. The gap-graded test results approach the values obtained for the coarsest gradation in the variable exponential series.

The next variation in gradation was obtained by eliminating the material passing the No. 4 sieve and retained on the No. 8 sieve, from the maximum density gradation of n = .375. A series of three gap-graded mixtures were obtained by distributing the material eliminated by three different methods. A coarse mix was obtained by distributing the eliminated fraction proportionally throughout the sizes larger than the eliminated fraction; a fine mix was obtained by distributing the eliminated fraction proportionally throughout the sizes smaller than the eliminated fraction; and the third gradation was obtained by distributing the eliminated fraction proportionally throughout all the remaining sizes. The gradations obtained and the test results are shown in Table XII. The gradation obtained by distributing the eliminated fraction throughout the remaining sizes has the highest density and lowest voids of the series. It is interesting to note also that all three of the gap-gradations have higher densities and lower void contents than the corresponding values for the maximum density gradation for the variable exponent series.

Another series of gap-graded mixtures was obtained by eliminating two fractions of material from the maximum density gradation of n = .375; material passing the No. 30 sieve and retained on the No. 50 sieve, and material passing the No. 50 sieve and retained on the No. 100 sieve. Three gradations were obtained by distributing the eliminated fractions in the same manner as for the previous gap-graded series. The coarse mix was discarded however, because its gradation was very similar to that of the gradation obtained by distributing the eliminated fraction proportionally throughout the remaining sizes. The gradations used and the test results are shown in Table XIII. It can be seen that the densities and void contents are very close to the corresponding values of the maximum density gradation for the variable exponent series. The fine mix had a slightly higher density and slightly lower void content than the corresponding values for the other gap-gradation of the series, and the maximum density gradation of the variable exponent series, which had essentially the same values.

Although some of the gap-gradations had a higher maximum density than the maximum density gradation for the variable exponent series, the objective of testing the gap-gradations was not necessarily to obtain a higher maximum density; but rather to determine if there might be a highly significant change in density when some of the size fractions were eliminated because of the unusual combinations of flat and elongated particles, angularity, and smooth surface texture found in crushed bottle glass. No large change was found however due to elimination of one or two particle sizes.

B. Design of Mixture Meeting Marshall Requirements

Using crushed bottle glass as the aggregate and the maximum density gradation corresponding to an exponent of n = 0.375, a series of Marshall specimens were made to determine the optimum asphalt content. As was mentioned previously, it was not known if the maximum density gradation would make a satisfactory bituminous mixture; however, it was used as a starting point and modified as needed. The gradation is shown again in Table XIV as Gradation No. 1.

Five asphalt contents were selected in 0.5 increments from 4.0 to 6.0 percent (total weight basis), and three specimens were made for each asphalt content. The specimens were made at three different times with one specimen at each asphalt content being made at a given time. Fifty blow compaction was used and after cooling the specimens, bulk specific gravity, stability, and flow were determined.

The Marshall test results of the specimens made from the maximum density gradation of n = 0.375 are given in Table XV and plotted in Figure 9 for Trial Mix 1. As can be seen in Figure 9, there was no asphalt content at which all the data would satisfy the Asphalt

Institute's suggested Marshall design criteria shown in Table XVI. Stability was adequate for all asphalt contents, and flow was adequate up to almost 6.0 percent; however, there was no asphalt content at which the requirements of both percent air voids and percent voids in the mineral aggregate could be met. Therefore, it became necessary to modify the maximum density gradation in such a manner as to increase both the percent air voids and percent voids in the mineral aggregate while maintaining adequate stability and flow.

For a dense-graded bituminous mixture, Lefebvre (9) found three alternatives for increasing the percentage of voids in the mineral aggregate:

a) To increase the percentage of fine aggregate

b) To increase the percentage of intermediate sizes in the fine aggregate

c) To decrease the percentage of mineral filler

Campen, Smith, Erickson, and Mertz (14) found that the voids decrease with the addition of well graded coarse aggregate to well graded fine aggregate until a critical combination is reached. After that the voids increase.

Several modifications of the maximum density gradation were investigated before one was found that satisfied the Marshall criteria. All of the subsequent trial mixes were made and tested in the same manner as the initial trial mix. All of the modified gradations are given in Table XIV and the test results are shown in Table XV. It should be noted that most of the trial mixes were run for only one asphalt content. The trial mix was first run for a low asphalt content, and if the percent air voids were low for the low asphalt content, they would definitely be too low for a higher asphalt content, even though the percent voids in the mineral aggregate may increase with higher asphalt contents.

Gradations No. 2 and No. 3 contained less mineral filler, but the trial mixes produced lower air voids and voids in the mineral aggregate than the initial gradation for the equivalent asphalt content. Gradation No. 2 contained more coarse material, and gradation No. 3 more intermediate fine meterial than the initial gradation, but trial mixes 2 and 3 had almost the same air voids and voids in the mineral aggregate. Because of this, it was thought that the initial gradation had such a high dust content that the mineral filler had passed the stage of being a filler and was actually creating voids when used in a bituminous mixture; thus, the decrease in voids and increase in unit weight of the Marshall specimens when some of the mineral filler was taken out. If this were the case, the dry density tests would not be a good indicator of density obtained in asphaltic mixtures.

Trial Mix 4 was run in view of this possibility. Gradation No. 4 is the gradation obtained when an exponent of 0.55 was used. Marshall specimens using this gradation had a higher density than the specimens using gradation No. 1, even though the gradation No. 1 had a significantly higher dry density. This points out that the dry density is not a good indicator of density obtained from asphaltic mixtures.

In gradation No. 5, mineral filler was reduced by 10 percent and the percentage of intermediate size fine aggregate was increased. The results of Trial Mix 5 showed that, for an asphalt content of 4.5 percent, the percent air voids had increased to an acceptable value, but the percent voids in the mineral aggregate were low. When the asphalt content was increased to a point where the voids in the mineral aggregate were acceptable, both the void content and the stability dropped to unacceptable values. Although gradation No. 5 did not produce a trial mix meeting Marshall criteria, the trial mix results did agree with the findings of Lefebvre (9).

Trial Mix 6 was conducted to determine the effect of a change in coarse aggregate on the void content and voids in the mineral aggregate. Gradation No. 6 contained 10 percent less mineral filler than the initial gradation, but a 10 percent increase in coarse aggregate. Results of Trial Mix 6 show a decrease in percent air voids and percent voids in the mineral aggregate, which agrees with the findings of Campen, Smith, Erickson, and Mertz (14).

Gradation No. 7 was arrived at by combining all of the changes found to increase the air voids and voids in the mineral aggregate of the Marshall specimens. The amount of coarse aggregate and mineral filler was decreased while the amount of intermediate fine aggregate was increased. Results of Trial Mix 7 show a very significant increase in percent air voids and percent voids in the mineral aggregate; in fact, the air voids were too high. Although the percent air voids did decrease with an increase in asphalt content, it was obvious that this gradation would not produce a mixture satisfying the stability and flow requirements.

Gradation No. 8 modified the initial gradation in the same manner as Gradation No. 7 except that the coarse aggregate was decreased by only half the amount. Results of Trial Mix 8 appeared promising enough to run a series to determine the optimum asphalt content.

For the series of Trial Mix 8, six asphalt contents were selected in 0.5 increments for 3.5 to 6.0 percent (total weight basis) in an attempt to get a better distribution of data about the projected optimum asphalt content.

The Marshall test results of the series of specimens made from gradation No. 8 are given in Table XV and plotted in Figure 10. All Marshall design criteria were satisfied with an asphalt content of 5.25 percent on a total weight basis.

C. Effects of Angularity and Sphericity Upon Marshall Properties

A series of Marshall specimens were made using gradation No. 8 and the previously determined optimum asphalt content of 5.25 percent. Four different combinations of glass were used. Mixes A, B, and C all contained crushed bottle glass in sizes smaller than a No. 8 sieve but bottle glass coarse aggregate was used in Mix A, drain cullet and tempered glass coarse aggregate were used in Mix B, and glass spheres were used as coarse aggregate in Mix C. The aggregate for Mix D consisted entirely of glass spheres. The mixture compositions and test results are summarized in Table XVII, as series 1. There were only small differences between the Marshall properties of the all bottle glass mixture and the mixture containing drain cullet and tempered glass in the coarse fractions. This indicates that the sphericity of the coarse particles has little effect upon the properties of an asphaltic mixture, at least for the range of aggregate sizes and sphericity investigated.

There was a considerable change in the Marshall properties when glass spheres were substituted for bottle glass in the coarse sizes, indicating that the angularity of the coarse aggregate has a significant effect upon the properties of an asphaltic mixture. The flow increased while the stability and void content decreased. These changes are probably due to the lack of interlocking resistance developed between particles in the coarse sizes.

When bottle glass was replaced by glass spheres in all sizes, the effects of interlocking resistance was illustrated rather dramatically. A very "soupy" mixture that was able to flow under its own weight was obtained and had a strength so low that stability and flow could not be measured. The high void content is due to the fact that the mixture was not compacting under the impact hammer but rather, rebounding after each blow, thereby receiving very little compaction.

In order to obtain more information concerning the affects of angularity and sphericity, a second series of Marshall specimens were made using gradation No. 4, which contained more coarse aggregate than gradation No. 8. It was known that this gradation would not produce a mixture meeting Marshall specifications but it was desirable to know whether the same relationship between angularity, sphericity, and Marshall properties would hold for differing gradations. The results of the Marshall tests are shown in Table XVII, as series 2. Once again the Marshall properties of mixtures containing drain cullet and tempered glass coarse aggregate were similar to mixtures using bottle glass in the coarse sizes. This again indicates that the sphericity of the coarse particles has little effect upon the properties of an asphaltic mixture, within the range of aggregate size and sphericity investigated.

The substitution of glass spheres for bottle glass in the coarse sizes again produced an asphaltic mixture which had a higher flow, but lower stability and void content due to the lack of interlocking resistance developed between coarse particles.

No more specimens consisting entirely of glass spheres aggregate were made because of the unsuitable mixtures obtained at an asphalt content of 5.25 percent.

D. Application of Experimental Results

In the initial research concerning use of waste glass as an aggregate in bituminous concrete (1), the gradation Foster chose was a modified form of one computed by using an exponent of 0.45 in the Talbot equation. At that time it was recognized that this exponent might not give maximum density and hence might result in lower stability than could be obtained with another exponent. In this research, different gradations corresponding to a wide range in exponents were used to obtain higher densities, but the resulting stability values were not higher than those obtained by Foster. In Series 8, at the optimum asphalt content of 5.25 percent the unit weight was 139.7 pcf with a stability of 750 pounds. Foster obtained a unit weight of 139.5 pcf and a stability of 760 pounds at the 5.5 percent optimum asphalt content. The gradations differed primarily in that Series 8 specimens had more material passing the No. 8 sieve and retained on the No. 30. In Series 1, at the optimum asphalt content of 4.5 percent, unit weight was 142 pcf and stability was 1000 pounds. However, this mixture did not satisfy the voids requirements. Thus, attempting to improve the stability characteristics of glass-asphalt mixtures by altering the gradation does not appear to be feasible since the void content falls below acceptable values when higher density mixtures are used.

The fact that a large percentage of particles in the coarse fraction of crushed glass are flat, also appears to have little effect upon the Marshall properties of glass-asphalt mixtures. Angularity is more important than sphericity in determining stability characteristics. Thus, the presence of a large percentage of flat particles in the coarse fraction should not be cause for concern with respect to their effects upon Marshall properties.

For the method of crushing used in this research, the percentage of flat and elongated particles in the finer glass sizes was relatively small. A quantitative determination of the percent flats was not conducted for material finer than a No. 50 sieve due to difficulties in handling and measuring particles of this size, but for material between a No. 4 and No. 50 sieve, the percent flats ranged only from 6 to 12 percent. However, in a Canadian installation of glasphalt (15) using glass crushed by a different method, particle counts indicated that large percentages of flat and elongated particles were present in the finer size fractions. Also, Foster used a different method for crushing the bottles and his data also shows higher percentages of flats in the fines. The effect of flat particles in the fine fraction was not assessed in this investigation but should probably be studied in light of this information.

V. CONCLUSIONS AND RECOMMENDED FURTHER RESEARCH

Based upon the laboratory work carried out in this study, the following conclusions have been reached:

1. For a dense-graded dry aggregate, the angularity and sphericity of the glass particles affect the gradation that will give maximum density. This is true whether the aggregate consists entirely of glass or contains glass in the coarse fractions only. For an all-glass aggregate, a mixture of angular particles, such as crushed bottle glass containing a high percentage of flat and/or elongated particles, will have a maximum density gradation containing a higher precentage of fines than the maximum density gradation for a spherical, non-angular aggregate such as glass spheres. When coarse sized glass aggregate is used in combination with smaller sized conventional aggregate, the maximum density gradation is affected in much the same way as the maximum density gradation for the all-glass aggregate, but to a lesser extent. The more angular the glass particles, the larger the percentage of fines necessary for the maximum density gradation; while the more spherical the glass particles, the wider is the range of gradations giving maximum density, or close to it.

2. For a dense graded dry aggregate, the angularity and sphericity of the glass particles also affect the void content of the maximum density gradation. For a maximum density gradation consisting entirely of glass aggregate, the void content will be more than twice as high for angular, non-spherical particles, such as crushed bottle glass, than for highly spherical, non-angular particles such as glass spheres. When

coarse sized glass aggregates are used in combination with smaller sized conventional aggregates, much the same results are obtained, but with not nearly as large a difference in voids, thus indicating that the void content of the maximum density gradation is more dependent on the shape of the fine particles than on the shape of the coarse particles. The properties of angularity and sphericity seem to have about an equal effect on the void content of the maximum density gradation.

3. The maximum density gradation for crushed bottle glass obtained by varying the exponent in Talbot's equation does not produce an asphaltic mixture meeting Marshall design requirements because of low void contents. However, the maximum density gradation can be modified to produce an asphaltic mixture meeting these requirements by decreasing the amount of coarse aggregate and mineral filler while increasing the amount of intermediate fine aggregate.

4. Dry density tests for dense-graded aggregate do not give a good indication of densities obtained in asphaltic mixtures using the same aggregate. One gradation may have a lower dry density than another, yet have a higher density when both are used in an asphaltic mixture.

5. For coarse sized glass aggregate, the sphericity of the glass particles has little effect upon the Marshall properties of the asphaltic mixture. However the angularity of coarse sized glass aggregate definitely affects the Marshall properties of the asphaltic mixture; a loss of angularity significantly decreases the stability and void content, while increasing the flow. The angularity of fine sized glass aggregate appears to have an even more important influence on the

asphaltic mixture's properties than does the angularity of the coarse sized glass aggregate. A loss of angularity in all sizes of the glass aggregate for an asphaltic mixture essentially reduces the strength of the mixture to zero. The strength of a glass aggregate asphaltic mixture appears to derive almost entirely from the interlocking resistance developed between particles.

A further study of the effects of angularity and sphericity of the fine sized glass aggregate upon a mixture's Marshall properties would widen the basis of inference for conclusion concerning the source of strength for glass aggregate asphaltic mixtures.

A study of the effects of angularity and sphericity of the glass aggregate upon the Marshall properties of an asphaltic mixture, when the mixture is a combination of glass and conventional aggregate, should be very beneficial since most of the field installations consist of such a combination. The effects of both coarse and fine glass aggregate should be investigated.

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VITA

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The author is married to the former Mary Elaine Woody of Meta, Missouri.

APPENDICES

APPENDIX A

Figures

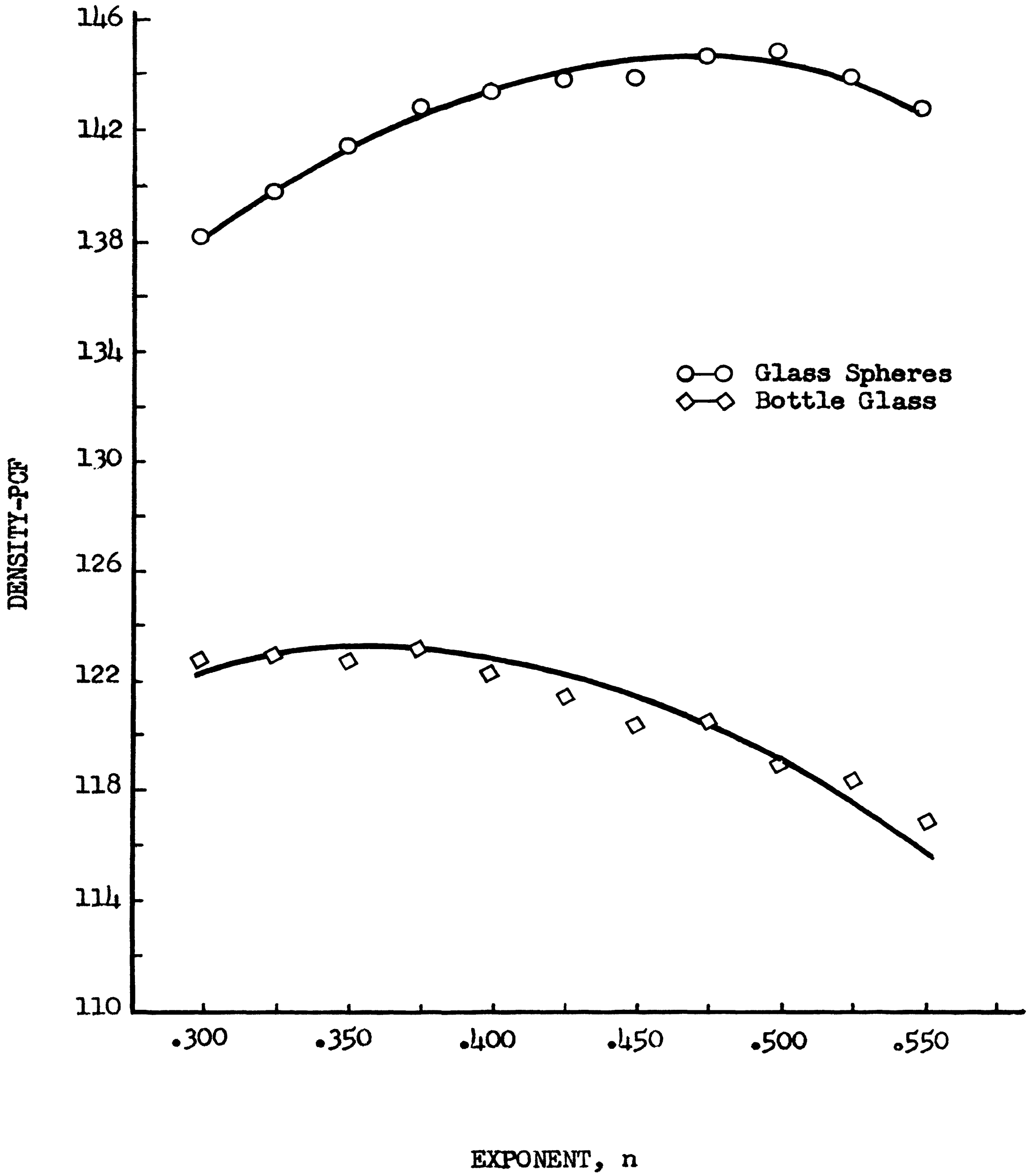

Figure 1. Density of Crushed Bottle Glass and Glass Spheres For Variable Grading Ratio

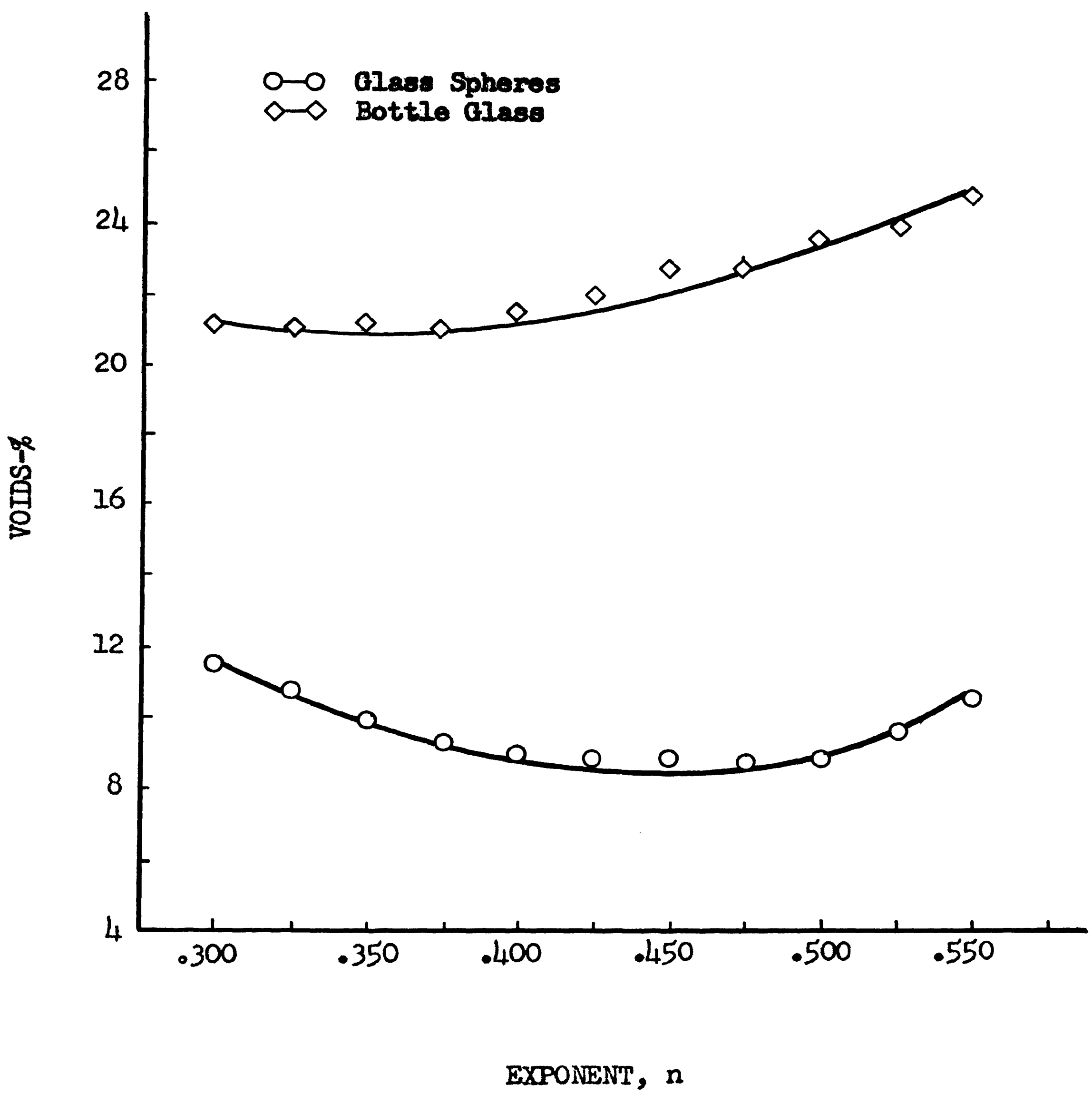

Figure 2. Voids of Crushed Bottle Glass And Glass Spheres For Variable Grading Ratio

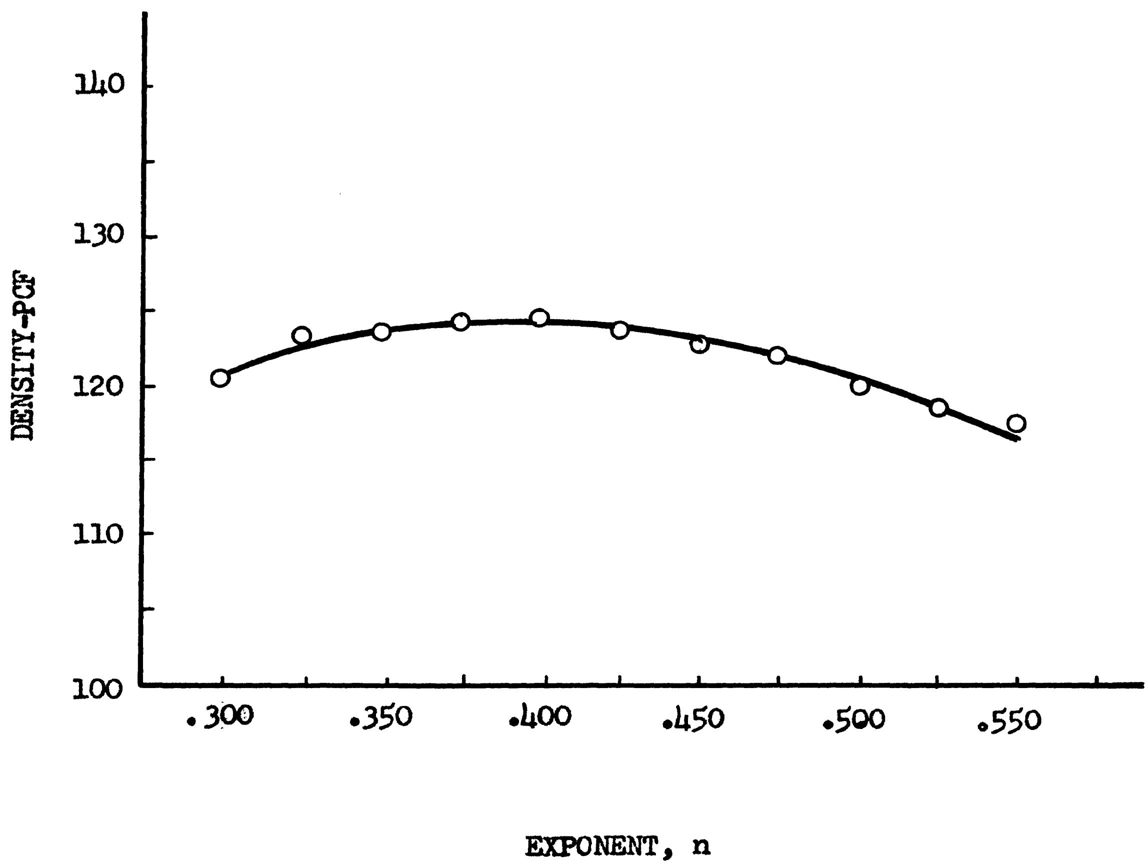

Figure 3. Density of Bottle Glass-River Sand-Mineral Filler Combination For Variable Grading Ratio

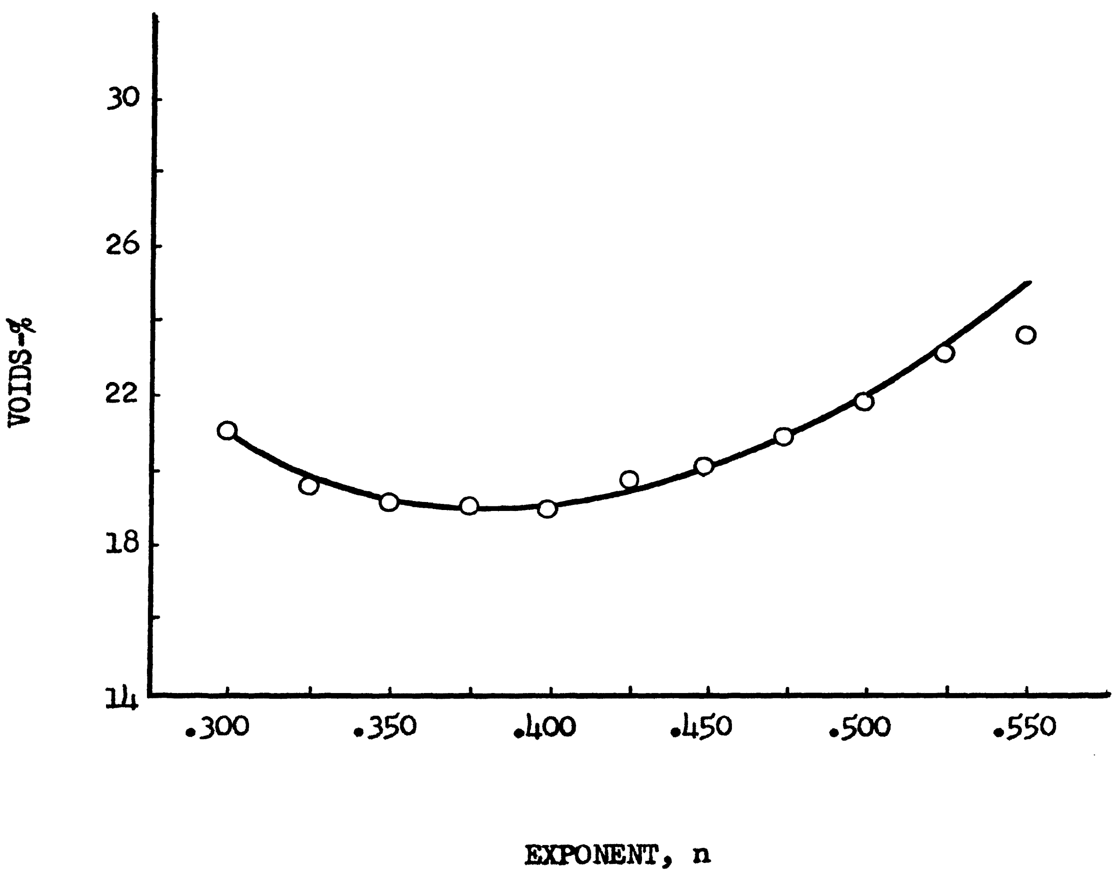

Figure 4. Voids of Bottle Glass-River Sand-Mineral Filler Combination For Variable Grading Ratio

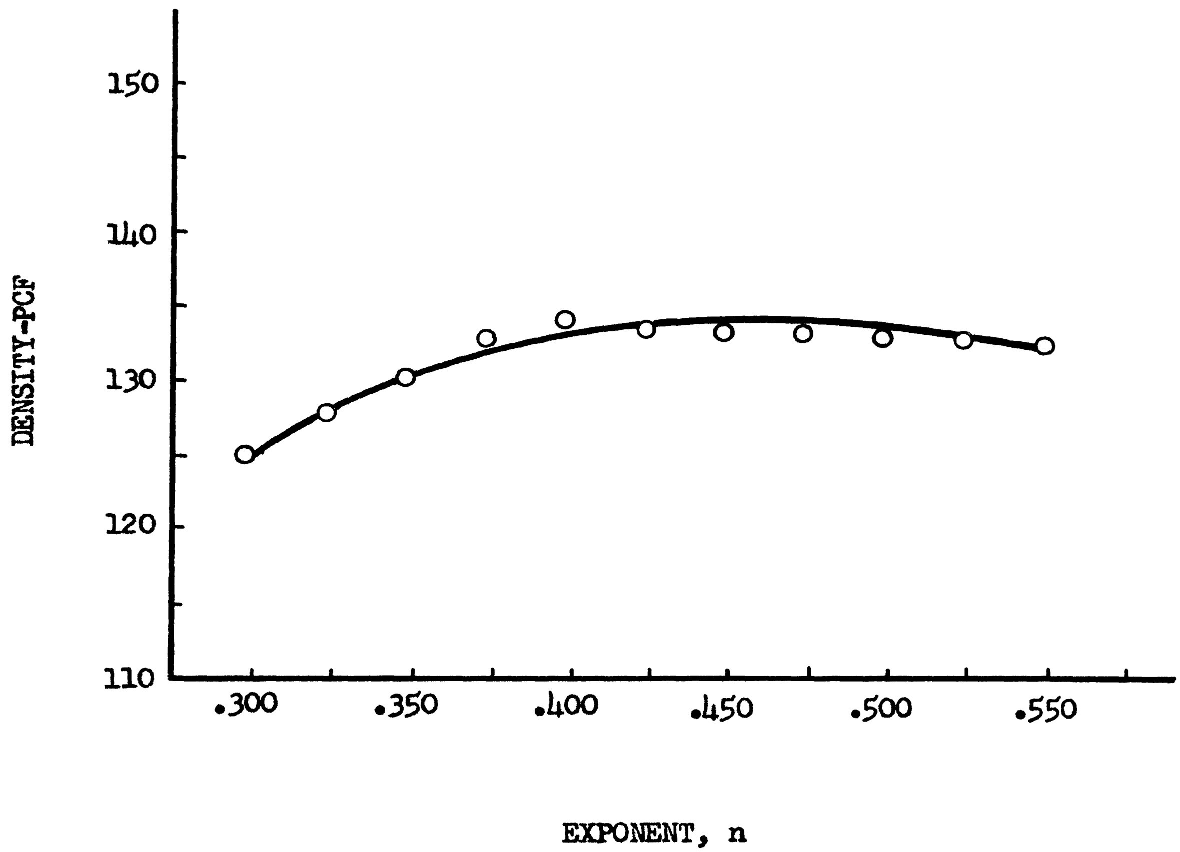

Figure 5. Density of Glass Spheres-River Sand-Mineral Filler Combination For Variable Grading Ratio

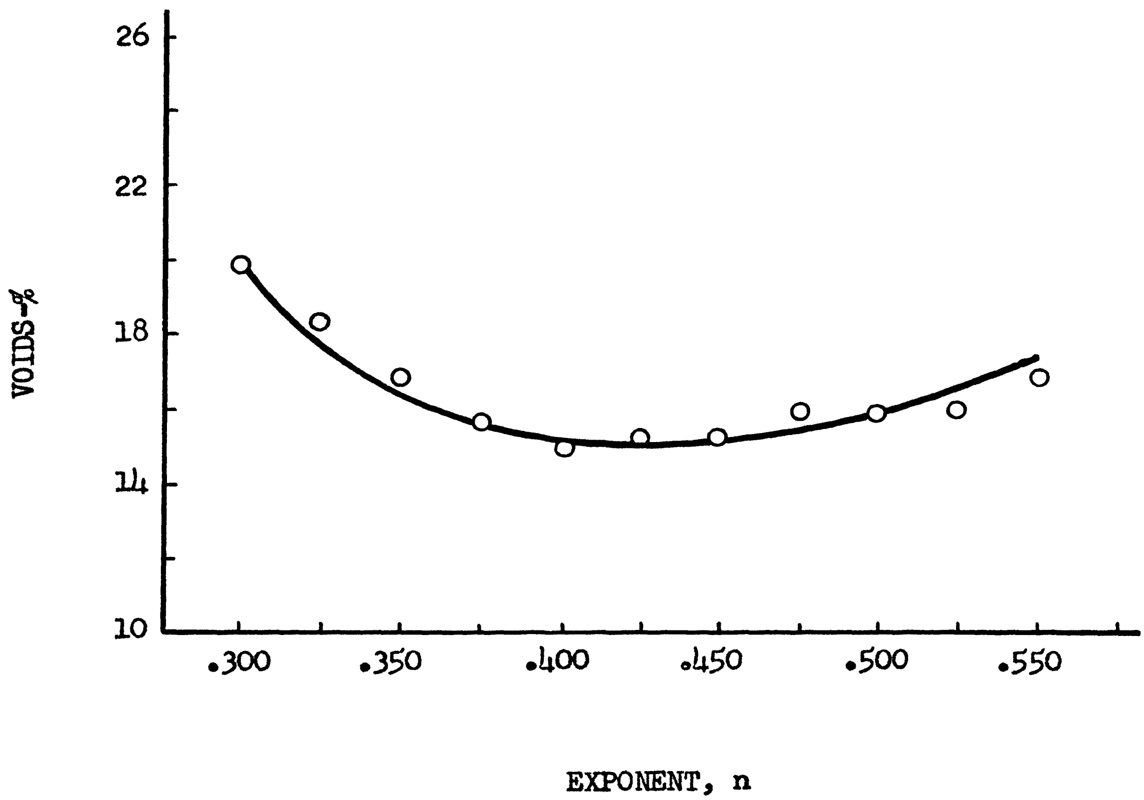

Figure 6. Voids of Glass Spheres-River Sand-Mineral Filler Combination For Variable Grading Ratio

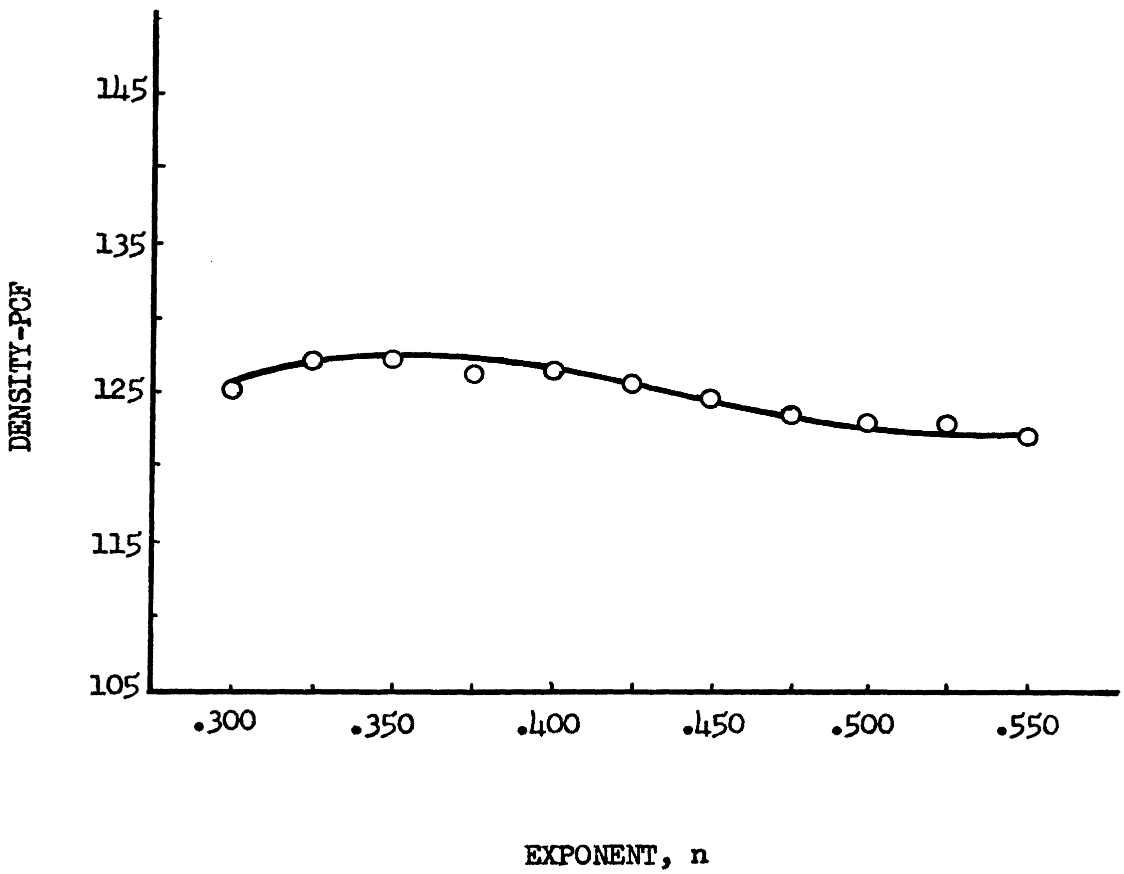

Figure 7. Density of Drain Cullet-Tempered Glass-River Sand-Mineral Filler Combination For Variable Grading Ratio

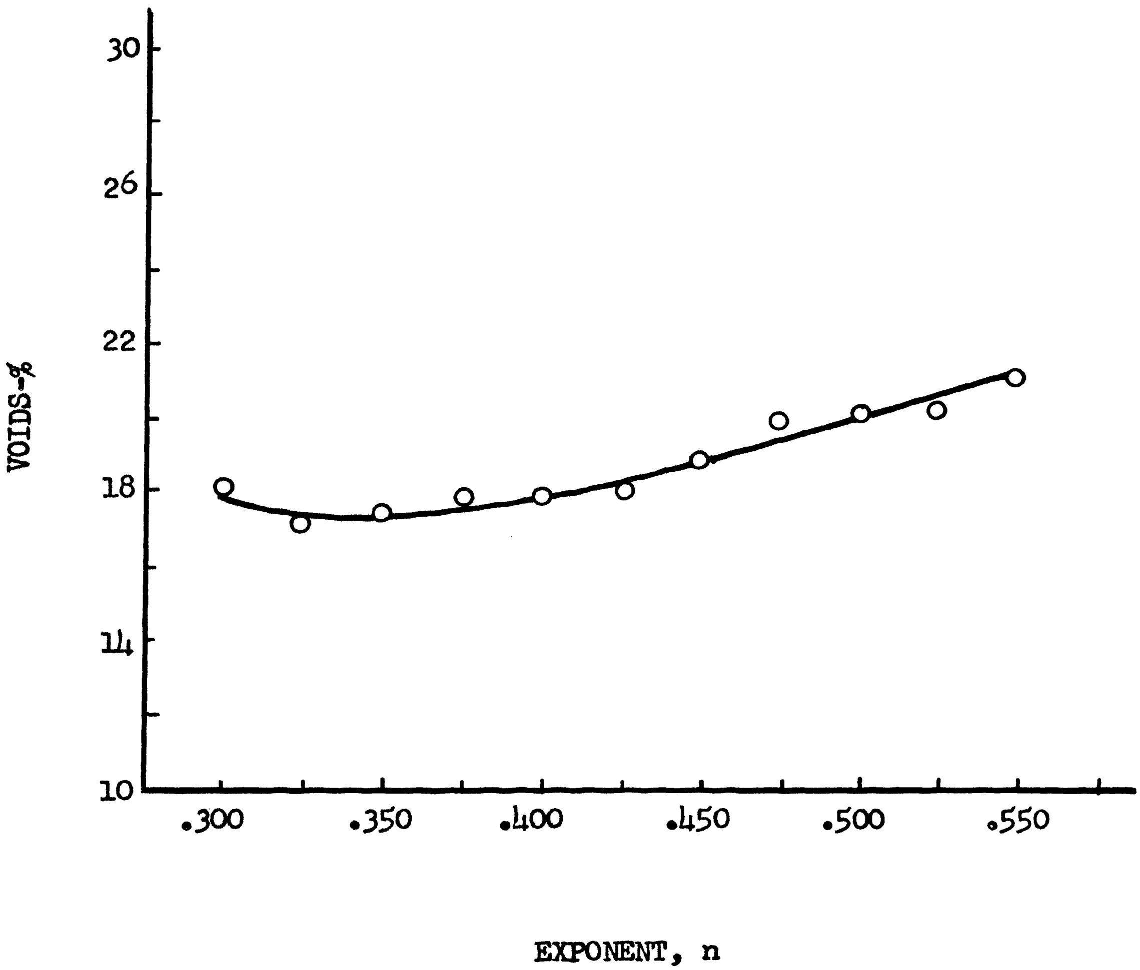

Figure 8. Voids of Drain Cullet-Tempered Glass-River Sand-Mineral Filler Combination For Variable Grading Ratio

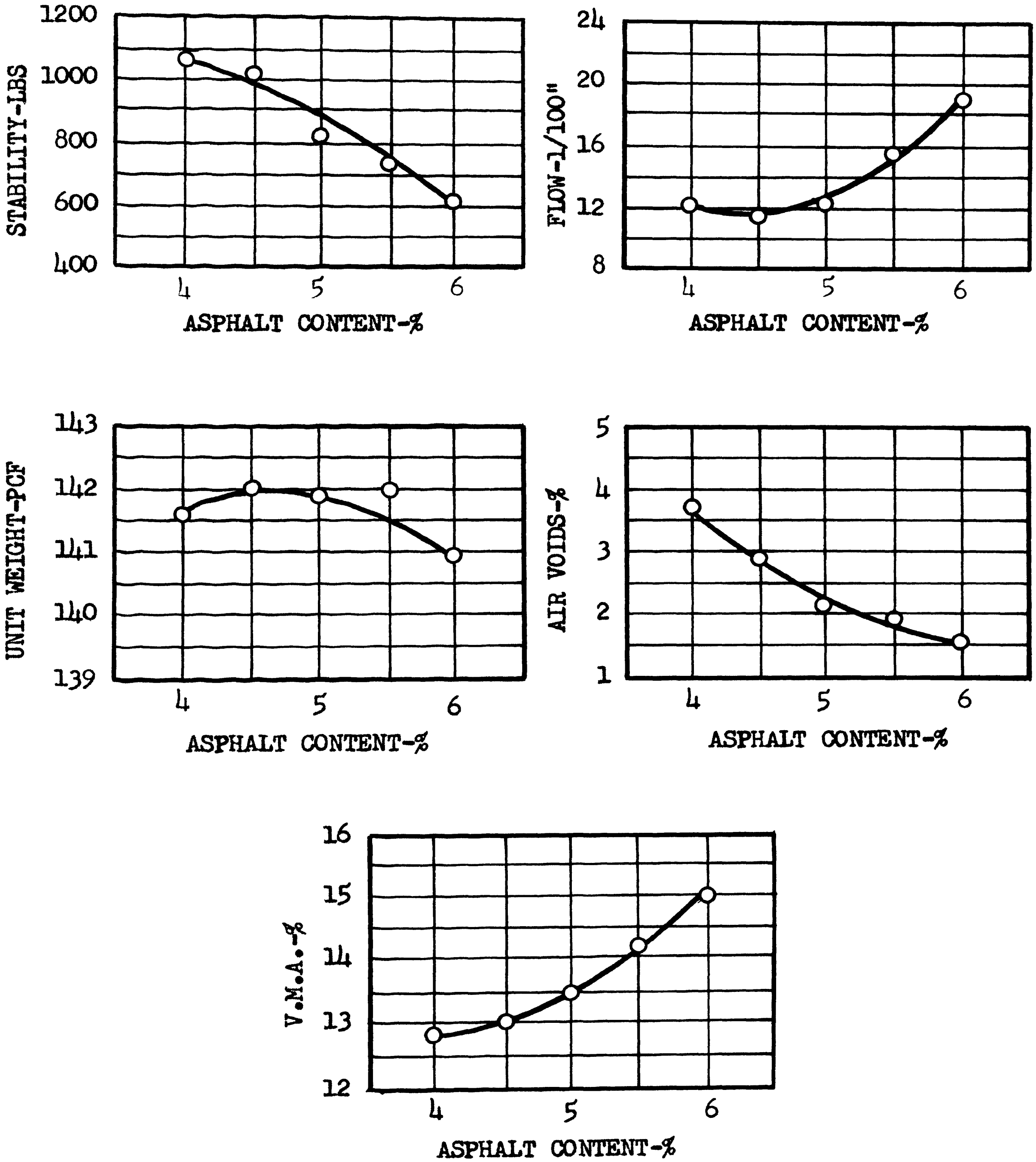

Figure 9. Marshall Test Property Curves-Trial Mix 1

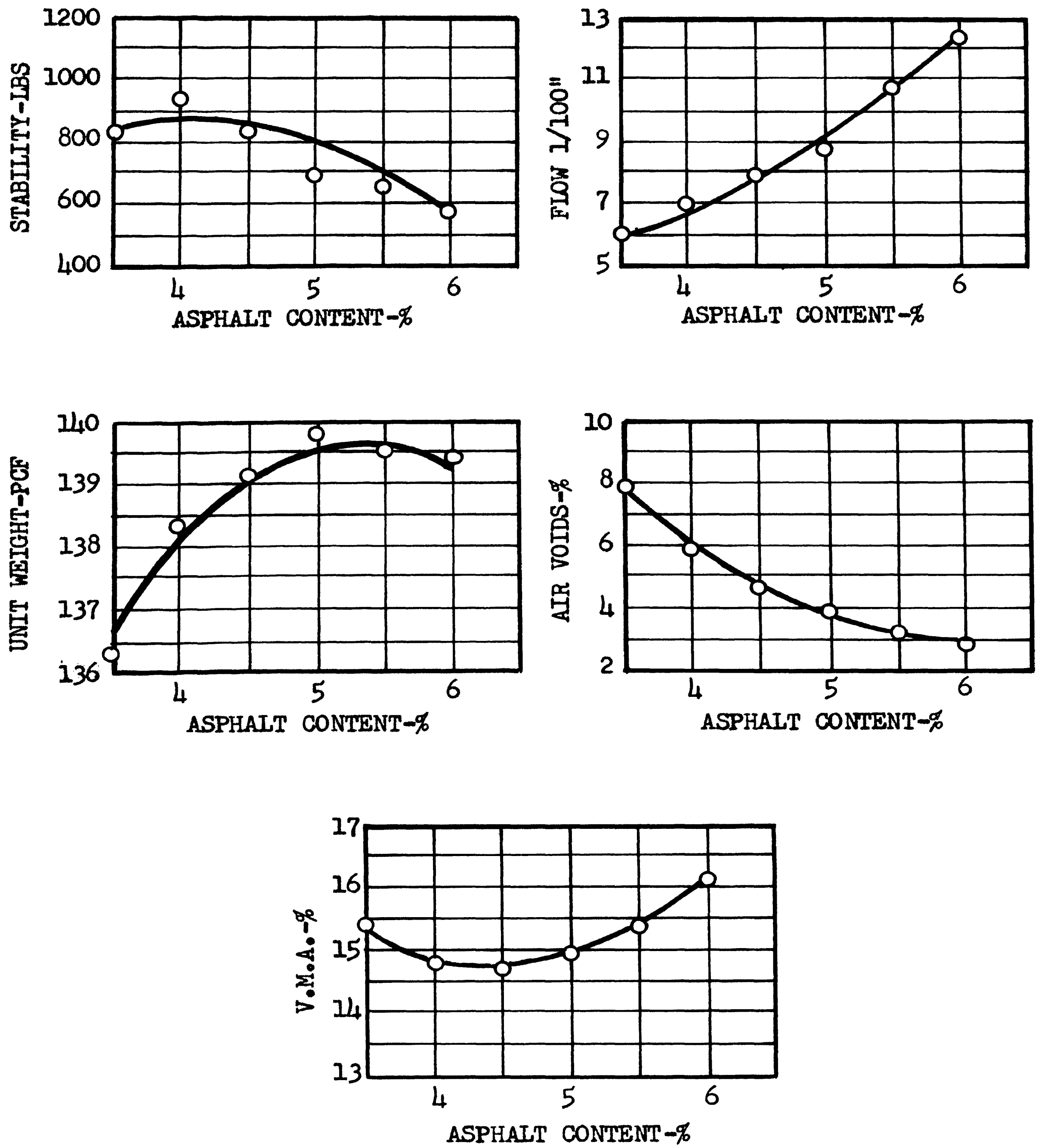

Figure 10. Marshall Test Property Curves-Trial Mix 8

APPENDIX B

Tables

TABLE I

BULK SPECIFIC GRAVITIES OF AGGREGATES

Type of Aggregate	Bulk Specific Gravity
Crushed Bottle Glass	2.50
Glass Spheres All Sizes[a]	--
Glass Spheres Coarse Sizes[b]	2.62
Drain Cullet and Crushed Tempered Glass	2.50
Meramec River Sand and Limestone Dust	2.45

[a]BSG varied with change in gradation
BSG = 2.50 for n = .300
BSG = 2.53 for n = .425
BSG = 2.56 for n = .550

[b]Coarse sizes pertain to all material larger than the No. 16 sieve.

TABLE II

FLAT AND ELONGATED PARTICLE COUNT

FLAT AND ELONGATED PARTICLE COUNT FOR CRUSHED BOTTLE GLASS

Sieve Size		Number Counted	Percent in Each Classification			
Passing	Retained		Flat[a]	Elong.[b]	Flat & Elong.	Not Flat or Elong.
1/2"	3/8"	137	77	1	0	22
3/8"	No. 4	224	36	1	0	63
No. 4	No. 8	423	6	0	1	93
No. 8	No. 16	474	9	0	0	91
No. 16	No. 30	303	12	1	0	87
No. 30	No. 50	314	11	1	0	88

FLAT AND ELONGATED PARTICLE COUNT FOR DRAIN CULLET AND CRUSHED TEMPERED GLASS

Sieve Size		Number Counted	Percent in Each Classification			
Passing	Retained		Flat[a]	Elong.[b]	Flat & Elong.	Not Flat or Elong.
1/2"	3/8"	102	0	0	0	100
3/8"	No. 4	107	0	2	0	98
No. 4	No. 8	313	0	1	0	99
No. 8	No. 16	370	12	0	0	88

[a] Width/Thickness greater than 3.0

[b] Length/Width greater than 3.0

TABLE III

PROPERTIES OF ASPHALT*

Specific Gravity @ 60F	1.011
Penetration @ 77F	90
Viscosity S.S.F. @ 275F	143.5
Flash, °F, Cleveland Open Cup	590
Solubility in CCl_4, %W	99.93
Ductility @ 77F, cm.	150+

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[a] Furnished through courtesy of Shell Oil Company

TABLE IV

GRADATIONS OF DRY DENSITY TESTS
VARIABLE GRADING RATIO

Sieve Size	Percent Passing Given Sieve For Values of Exponent "n"										
	.300	.325	.350	.375	.400	.425	.450	.475	.500	.525	.550
1/2"	100	100	100	100	100	100	100	100	100	100	100
3/8"	92	91	90	90	89	89	88	87	87	86	85
No. 4	74	72	70	69	67	65	64	62	61	59	58
No. 8	61	59	56	54	52	50	48	46	44	42	41
No. 16	50	47	44	42	39	37	35	33	31	30	28
No. 30	40	37	34	32	29	27	25	23	22	20	18
No. 50	32	29	27	24	22	20	18	17	15	14	13
No. 100	26	24	21	19	17	15	14	12	11	10	9
No. 200	21	19	16	14	13	11	10	9	8	7	6

TABLE V

DENSITY AND PERCENT VOIDS
FOR CRUSHED BOTTLE GLASS*
VARIABLE GRADING RATIO

Exponent "n"	Density (PCF)	Voids (%)
.300	123.0	21.2
.325	123.0	21.2
.350	122.7	21.3
.375	123.3	21.0
.400	122.3	21.6
.425	121.6	22.1
.450	120.4	22.8
.475	120.5	22.8
.500	118.8	23.8
.525	118.4	24.1
.550	116.8	25.1

*Average of three tests

TABLE VI

DENSITY AND PERCENT VOIDS
FOR GLASS SPHERES*
VARIABLE GRADING RATIO

Exponent "n"	Density (PCF)	Voids (%)
.300	138.1	11.5
.325	139.7	10.8
.350	141.4	9.9
.375	142.9	9.1
.400	143.4	9.0
.425	144.0	8.8
.450	144.0	8.9
.475	144.8	8.6
.500	144.9	8.8
.525	143.8	9.6
.550	142.7	10.7

*Average of three tests

TABLE VII

COMBINATIONS OF AGGREGATES FOR DRY DENSITY TESTS VARIABLE GRADING RATIO

Sieve Size		Combinations of Aggregate		
Passing	Retained			
1/2"	3/8"	Bottle Glass	Glass Spheres	Drain Cullet
3/8"	No. 4	Bottle Glass	Glass Spheres	Tempered Glass
No. 4	No. 8	Bottle Glass	Glass Spheres	Tempered Glass
No. 8	No. 16	Meramec River Sand	Meramec River Sand	Meramec River Sand
No. 16	No. 30	Meramec River Sand	Meramec River Sand	Meramec River Sand
No. 30	No. 50	Meramec River Sand	Meramec River Sand	Meramec River Sand
No. 50	No. 100	Meramec River Sand	Meramec River Sand	Meramec River Sand
No. 100	No. 200	Meramec River Sand	Meramec River Sand	Meramec River Sand
No. 200	PAN	Mineral Filler (Limestone Dust)	Mineral Filler (Limestone Dust)	Mineral Filler (Limestone Dust)

TABLE VIII

DENSITY AND PERCENT VOIDS
FOR BOTTLE GLASS-RIVER SAND-
MINERAL FILLER COMBINATION*
VARIABLE GRADING RATIO

Exponent "n"	Density (PCF)	Voids (%)
.300	121.0	21.2
.325	123.5	19.5
.350	124.1	19.3
.375	124.5	19.1
.400	124.8	19.0
.425	123.6	19.8
.450	123.0	20.2
.475	122.1	20.9
.500	120.4	22.0
.525	118.8	23.3
.550	118.1	23.7

*Average of three tests

TABLE IX

DENSITY AND PERCENT VOIDS FOR GLASS SPHERES-RIVER SAND-MINERAL FILLER COMBINATION* VARIABLE GRADING RATIO

Exponent "n"	Density (PCF)	Voids (%)
.300	125.4	19.9
.325	127.8	18.4
.350	130.5	16.8
.375	132.8	15.5
.400	134.1	14.9
.425	133.5	15.3
.450	133.3	15.4
.475	133.4	15.5
.500	132.9	16.0
.525	133.0	16.1
.550	132.0	16.7

*Average of three tests

TABLE X

DENSITY AND PERCENT VOIDS
FOR DRAIN CULLET-TEMPERED GLASS-RIVER
SAND-MINERAL FILLER COMBINATION*
VARIABLE GRADING RATIO

Exponent "n"	Density (PCF)	Voids (%)
.300	125.5	18.2
.325	127.2	17.1
.350	127.1	17.4
.375	126.3	17.9
.400	126.6	17.8
.425	126.0	18.2
.450	125.2	18.8
.475	123.9	19.8
.500	123.4	20.1
.525	123.5	20.2
.550	122.4	20.9

*Average of three tests

TABLE XI

GRADATION AND DRY DENSITY TEST RESULTS
FOR GAP-GRADATION "A"

Sieve Size	Gradation "A" Percent Passing
1/2"	100
3/8"	100
No. 4	75
No. 8	75
No. 16	75
No. 30	25
No. 50	25
No. 100	25
No. 200	0

	Density* (PCF)	Voids* (%)
Gradation "A"	115.9	25.7

*Average of three tests

TABLE XII

GRADATIONS AND DRY DENSITY TEST RESULTS FOR GAP-GRADATIONS ELIMINATING MATERIAL PASSING NO. 4 SIEVE AND RETAINED ON NO. 8 SIEVE

Sieve Size	Gradation "B"[a] Percent Passing	Gradation "C"[b] Percent Passing	Gradation "D"[c] Percent Passing
1/2"	100	100	100
3/8"	85	90	88
No. 4	54	69	63
No. 8	54	69	63
No. 16	42	53	49
No. 30	32	40	37
No. 50	24	31	29
No. 100	19	24	22
No. 200	14	18	17

Gradation	Density[d] (PCF)	Voids[d] (%)
"B"	126.1	19.2
"C"	124.6	20.1
"D"	126.8	18.7

[a]Coarse Mix

[b]Fine Mix

[c]Eliminated fraction distributed throughout gradation

[d]Average of three tests

TABLE XIII

GRADATIONS AND DRY DENSITY TEST RESULTS FOR GAP-GRADATIONS ELIMINATING MATERIAL PASSING NO. 30 SIEVE AND RETAINED ON NO. 50 SIEVE, AND MATERIAL PASSING NO. 50 SIEVE AND RETAINED ON NO. 100 SIEVE

Sieve Size	Gradation "E"[a] Percent Passing	Gradation "F"[b] Percent Passing
1/2"	100	100
3/8"	90	88
No. 4	69	64
No. 8	54	47
No. 16	42	33
No. 30	32	22
No. 50	32	22
No. 100	32	22
No. 200	24	17

Gradation	Density[c] (PCF)	Voids[c] (%)
"E"	124.5	20.2
"F"	123.1	21.1

[a]Fine Mix

[b]Eliminated Fraction distributed throughout mix

[c]Average of three tests

TABLE XIV

GRADATIONS OF TRIAL MIXES

Sieve Size	Percent Passing Given Sieve For Gradations							
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
1/2"	100	100	100	100	100	100	100	100
3/8"	90	90	90	85	90	87	92	91
No. 4	69	69	69	58	69	62	73	71
No. 8	54	50	54	41	54	44	60	57
No. 16	42	38	42	28	42	32	48	45
No. 30	32	28	30	18	28	22	32	30
No. 50	24	20	22	13	18	15	20	19
No. 100	19	15	15	9	9	9	9	9
No. 200	14	10	11	6	5	5	5	5

TABLE XV

RESULTS OF MARSHALL TESTS
USING CRUSHED BOTTLE GLASS AGGREGATE*

Trial Mix	Asphalt Content (TWB)	Unit Weight (PCF)	Air Voids (%)	VMA (%)	Stability (LBS)	Flow ($\frac{1}{100}$ - IN)
1(Series)	4.0	141.6	3.70	12.79	1072	12.3
1 "	4.5	142.0	2.83	13.03	1016	11.7
1 "	5.0	141.9	2.22	13.49	818	12.3
1 "	5.5	142.0	1.89	14.19	745	15.5
1 "	6.0	140.9	1.55	15.02	624	19
2	4.5	142.7	2.34	12.59	920	12
3	4.5	142.8	2.23	12.49	1096	9.5
4	4.5	142.6	2.43	12.67	747	8.7
5	4.5	139.8	4.31	14.37	622	7.8
5	5.0	139.6	3.85	14.93	565	8.7
5	5.5	140.1	2.84	15.02	460	9.8
6	4.5	142.2	2.67	12.89	704	9.3
7	4.5	135.2	7.44	17.16	309	6.2
7	5.0	136.8	5.77	16.64	342	6.8
8	5.0	138.5	4.58	15.59	496	8.2
8(Series)	3.5	136.3	7.87	15.41	820	6.0
8 "	4.0	138.4	5.91	14.80	939	7.0
8 "	4.5	139.2	4.73	14.74	831	7.8
8 "	5.0	139.8	3.83	14.92	677	8.7
8 "	5.5	139.5	3.20	15.35	651	10.7
8 "	6.0	139.4	2.76	16.08	567	12.5

*Average of three specimens

TABLE XVI

MARSHALL DESIGN CRITERIA*

Test Property	Min	Max
Stability	500	---
Flow	8	18
% Air Voids (Surfacing)	3	5
% Voids in Mineral Aggregate (1/2" max size)	15	---

*Recommended by The Asphalt Institute for medium traffic (50 blow compaction)

TABLE XVII

GLASS AGGREGATE COMBINATIONS
AND THEIR MARSHALL TEST RESULTS

Sieve Size		Type of Glass Aggregate For Mix			
Passing	Retained	A	B	C	D
1/2"	3/8"	Bottle Glass	Drain Cullet	Glass Spheres	Glass Spheres
3/8"	No. 4	Bottle Glass	Temp. Glass	Glass Spheres	Glass Spheres
No. 4	No. 8	Bottle Glass	Temp. Glass	Glass Spheres	Glass Spheres
No. 8	No. 16	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 16	No. 30	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 30	No. 50	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 50	No. 100	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 100	No. 200	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 200	PAN	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres

Series	Combination	Asphalt Content (TWB)	Unit Weight* (PCF)	Air Voids* (%)	VMA* (%)	Stability* (LBS)	Flow* ($\frac{1}{100}$ - IN)
1	A	5.25	138.1	4.57	16.06	590	8.3
	B	5.25	137.8	4.79	16.26	562	8.7
	C	5.25	141.3	3.89	15.66	416	9.5
	D	5.25	140.9	6.82	18.54	---	---
2	A	5.25	142.4	1.57	13.42	705	12.2
	B	5.25	142.5	1.52	13.38	660	14.3
	C	5.25	146.6	1.13	13.32	436	17.0

*Average of three specimens